EXPEDIENT MILITARY AIRFIELDS IN COLD CLIMATES

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INTRODUCTION

The demands of winter warfare are daunting, and history is replete with stories of powerful military machines defeated by winter conditions: Charles XII, Napoleon Bonaparte, and Adolf Hitler come readily to mind as examples. Today's military engineer must be prepared to operate in any condition and anywhere in the world. The U.S. national objectives are increasingly requiring rapid deployment to unexpected, remote, and often very austere locations. In these missions, we are more dependent on airfields than ever before. Without them, we often have little ability to insert, sustain, and withdraw combat forces. The ability to seize, repair, expand, and build airfields is a major foundation component of modern military force projection.

Winter weather plays havoc with any airfield construction or repair. Frozen soils and aggregates may require blasting to excavate or loosen them, they are impossible to compact properly when frozen, thawing of frozen material may reduce them to the consistency of a thick gruel, freezing temperatures adversely affect almost all of our conventional paving materials such as asphaltic concrete or portland-cement concrete, and so on. While the military engineer may be called upon to provide airfield facilities in the winter, actually accomplishing the mission may prove a daunting undertaking.

For conventional construction, there are techniques such as new antifreeze admixtures for portland-cement concrete, accelerators for cement stabilization, and adjustments to normal construction practices that allow us to extend construction to temperatures well below commonly accepted construction norms. However, in this paper, we would like to address a more specific military engineering problem: how to provide an expedient airfield pavement for logistical aircraft under conditions of extended freezing weather. In this case, the military engineer has the opportunity to make the cold an ally instead of an enemy. There is little military guidance in this area now, but we feel that there are technologies that could be exploited to expand our military engineering capability for providing expedient military airfields under such conditions.

ICE AIRFIELDS

Ice roads are a fundamental transportation mode in many countries with cold winters and are standard infrastructure in oil, mineral, and timber industrial exploitation in the Arctic and Subarctic regions. Similarly, ice airfields are often a key winter transportation hub for remote villages and industrial activities in such regions. Construction of the DEW-Line radar system used ice airfields to support construction in the 1950s. In the Antarctic, ice runways provide crucial logistical infrastructure for U.S. scientific efforts and support C-130, C-141, C-5, and C-17 operations (Figure 1). A limited number of ski-equipped LC-130 aircraft are available from the New York Air National Guard. However, this limited resource is preferably used to support operations at snow airfields within Antarctica, and wheeled aircraft are preferred for the major logistical hauls from New Zealand to the ice runways at McMurdo Station. Ice airfields are a well-proven method of supporting wheeled military logistical aircraft, but the engineering involved is complex.

Ice is not a uniform product. Depending on freezing conditions, temperature, rate of loading, and test conditions, a variety of strengths may be measured. Flexural or tensile strength will vary from 50 to 300 psi depending on such factors. The ice itself is an anisotropic, highly viscoelastic material. Its strength and stiffness drops quickly as temperature rises and plummets near freezing. Ice fails ductilely or creeps under sustained or slow loads but is brittle under rapidly applied loads. Sea-ice is always weaker than fresh-water ice because of the salt content. Despite these complexities, ice can provide a usable structural surface for even the largest of military transports.

As a rough rule-of-thumb, a C-130 will require on the order of 4 ft of freshwater ice and 6 ft of sea ice to support operations (Crick and McClellen 1983). More precise analysis is possible using various numerical formulations (e.g., Vaudrey 1976, Barthelemy 1992) to calculate stresses and a comparison of these calculated stresses with some fatigue criteria. Figure 2 shows examples of such fatigue criteria for sea ice. Such analysis is dynamic rather than static however as the strength and stiffness of the ice is a function of the ice temperature. Hence analysis results will vary as temperatures change. One must also allow for creep under sustained load (Figure 3). This may be done either analytically (Vaudrey 1976) or by monitoring deformations under parked aircraft in the field. Ten percent maximum allowable deformation of the ice thickness is a commonly used criterion for floating ice. Design charts and guidance for military sea-ice runways are published (Vaudrey 1976 and Barthelemy 1992), and an updated engineering technical letter on the topic is currently being prepared by the US Army Cold Regions Research and Engineering Laboratory for publication by the Air Force Civil Engineering Support Agency.

Using simplified techniques proposed by Zarling (1978), one would estimate that approximately 9,000 freezing index ^{O}F-days would be required to form the required 4 feet of ice on a freshwater lake needed to support a C-130. Increased ice thicknesses needed for larger aircraft would require even more sustained cold weather. This essentially limits the potential for ice runways to northern Alaska and Canada in North America and northern Eurasia.

However, the ice formation can be accelerated in several ways. Once the ice is thick enough to support ground equipment, core holes can be drilled through the ice, and water can be flooded over the surface and allowed to freeze in small increments. A petroleum company has averaged 1.7 in./day of ice growth over a season in Alaska using this technique (private communication, Professor John Zarling, University of Alaska, August, 2002). Allowing roughly 1,000 freezing index ^{O}F-days to form the initial 6 in. or so of ice needed to support coring and pumping equipment, it would then be feasible to build another 42 in. of ice to support C-130 aircraft in 25 days using only drilling and pumping equipment. This would greatly expand the potential application to areas with less sustained cold winters.

This technique can be further accelerated if ice aggregate is spread over the ice or ground surface and then flooded. In this way, only the water in the ice aggregate voids has to be frozen greatly speeding the process. The ice aggregate can be mined from the ice surface not being used for the ice runway and supporting facilities. This could be done by cold-milling machines or cutting blocks of ice and crushing them in a conventional crushing plant. An alternate ice aggregate system with limited water addition has been demonstrated for roads and has the potential to build up to 2 miles of roadway per day in temperatures from near freezing to -40^{o}F (Fisher 1977, Freitag and McFadden 1997). Obviously, the production of the ice aggregate adds to the logistical difficulty of construction.

At temperatures below 0^{o}F, the oil industry has used a spray of water into the air to form a fine spray-ice aggregate. Pads up to 40-ft thick have been built at rates of feet per day ((private communication, Professor John Zarling, University of Alaska, August, 2002). Conceivably, this could be extended to provide ice aggregate or to build runways.

Ice runways have a proven history of supporting operations of heavy military logistical aircraft. This has included ice runways on glaciers, floating glacial ice sheets, and seasonal sea ice. However, if natural freezing alone is relied upon to form the needed ice thicknesses, ice runways are feasible in only limited areas of the far north. Recent innovations have the potential to allow construction of ice runways in several weeks to perhaps a few days. Construction of runways in the winter is very difficult, but ice-runway techniques offer an opportunity to provide operational flying surfaces in extreme cold. Without them, there is little prospect of preparing an operational airfield in such climates.

FROZEN GROUND

When ground freezes, frozen soil moisture becomes a cementing solid imparting strength and stiffness to the soil that it does not have when unfrozen. Fine-grained soils may have compressive strengths of a few hundred to over a thousand psi while coarse-grained soils may achieve appreciably higher strengths. Because the cementing agent is ice, strength is a function of temperature, and is subject to plastic creep just as in the preceding discussion of ice runways. It is important to recognize that the soil moisture is crucial. Without it, frozen ground is just cold dirt.

In order to contemplate running aircraft on frozen ground, we must ascertain its structural capacity. To illustrate how we might approach this problem, we will examine the possibility of taxiing and parking C-130 aircraft on the unsurfaced soil adjacent to the Hot Cargo Pad (Airfield Feature A-16) at Minot AFB, ND. The base is located in relatively level glacial-till plains with the upper 3 ft of soils typically being ML or CL soils with underlying CL soils (Howey et al 1974). The upper level soils are typically 60 to 75% fines with liquid limits commonly in the low 30s and the plasticity index in the upper teens. The lower soils are somewhat finer but similar. The equilibrium moisture content in these soils under paved areas is 13.0 to 13.6% with typical CBR values of 7 (Howey et al 1974, AFCESA 1974, 1998). Table 1 shows the predicted possible C-130 operations for different moisture conditions. Essentially, unless aircraft can operate on frozen soils, there is no prospect of operating aircraft here without paving, stabilizing, or overlaying the area with landing mats.

Minot winters are cold with the freezing season beginning in early November and lasting through late March. January is the coldest month with an average daily maximum of 18^{o}F and an average daily low of -4^{o}F. The mean length of the freezing season is 133 days with an air freezing index of 2,180^{o}F-days. Frost depths average 3.9 ft but have been measured to 6.2 ft.

Frozen fine-grained soils of moderate plasticity have modulus of elasticity values varying from 78,000 to 500,000 psi or more depending on test temperature, moisture content, and specific soil characteristics. These correspond to the modulus values one might expect of granular layers (25,000 to 100, 000 psi) or asphaltic concrete (100,000 to 1,000,000+ psi) in flexible pavements. Rigid concrete pavements usually have a modulus value in the range of 4 to 6 million psi. Given these relative modulus values, one would anticipate the frozen soil would behave and distribute load in a manner analogous to a flexible pavement rather than a rigid pavement. Frozen soils also tend to yield at relatively high strain levels, further suggesting that behavior will be similar to a flexible rather than a rigid pavement.

If one considers the frozen soil as a flexible pavement as its material properties suggest, then one could evaluate its structural capacity using the military's layered elastic analysis techniques for flexible pavements (Barker and Brabston 1975). The problem is essentially a two layer problem consisting of the upper frozen layer and the lower unfrozen layer. Each layer is modeled as linearly elastic, with the inherent limitations of such model assumptions, and is represented by a modulus of elasticity and a Poisson's ratio. The failure mode for flexible pavement analysis is rutting in the subgrade (and considering that the frozen soil strength is in the hundreds of psi, deformations from rapid loading should be minor in the frozen layer. To evaluate rutting failure, the vertical strain is computed at the surface of the subgrade, and this is compared with the allowable strain calculated as a function of repetitions of load and subgrade modulus. The specific equation for this subgrade criteria is provided in Barker and Brabston (1975) and is incorporated in the military layered elastic PCASE programs.

The BISAR layered elastic computer program was used for all calculations for the Minot AFB example. The subgrade was modeled with a modulus of elasticity of 10,500 psi (estimated as 1,500 x CBR, with CBR = 7). Two sets of calculations were made for the frozen layer with the modulus of elasticity as 100,000 and 450,000 psi, as approximate typical lower and upper values. Poisson's ration for both the frozen and unfrozen material was set as 0.4. Figure 4 shows the results of the calculations. For the lower-stiffness frozen material, the ground would have to be frozen to a depth of approximately 20 in. While for the stiffer 450,000-psi material only 10 in. of ground would be needed to frozen to support 10,000 passes (2,342 coverages) of a C-130.

The actual behavior of frozen ground is quite complex. The temperature of the frozen ground actually is a gradient with the bottom of the layer just at freezing and the rest reflecting ambient air temperature and diurnal swings in the temperature and thermal lag of temperature change within the frozen layer. The behavior and stiffness of the frozen soil is distinctly viscoelastic so that the actual stiffness of the layer is a function of temperature and rate of loading and not a simple elastic constant as represented. Also, there is a migration of water to the freezing front in fine-grained soil which will influence the moisture content of the bottom of the freezing layer, possible ice lense formation, increase of moisture in the soil near the freezing front, and possible dehydration of the lower unfrozen soil if there is not a source of water to provide a supply to the freezing front. However, all pavement analysis in practice uses simple representations from continuum mechanics and linear elasticity to represent very complex pavement material behavior. With the limited level of knowledge of the materials and site conditions, it is pragmatic to use simple models as with all pavement analysis and to conclude that when the ground has frozen to a depth of 10 to 20 inches, we can operate C-130 aircraft on it.

Next the modified Berggren equation was used to predict the depth of frost penetration for the 1994-1995 winter at Minot AFB. This equation is a simplification and approximation of more complex representations that is widely used in practice (e.g. Freitag and McFadden 1997, ASCE 1996). The freezing season for the 1994-1995 winter at Minot AFB began on 17 November 1994 and ended 10 April 1995. By the first of December, the calculated frost depth had penetrated past 10 inches and by mid-December it was past 20 inches. Consequently, this frozen soil could handle the required C-130 operations from early December until early April providing an operational window of approximately 4 months.

These analysis methods need refinement and verification but illustrate the approach and potential for frozen ground to support military logistical aircraft operations. Creep under parked aircraft must also be considered. If the site is under U.S. control prior to the onset of freezing grading and addition of moisture to the soil will enhance the utility of the unsurfaced facility.

SNOW RUNWAYS

Snow structure changes with time, temperature, solar radiation, and wind. Any disturbance of the snow also causes radical changes. These irreversible changes that occur after deposition are greatly enhanced by mechanical compaction. These changes are time and temperature dependent. Such changes are variously referred to as metamorphism, sintering, or age-hardening and can be supplemented with addition of water.

Compacted snow roads are a major winter transportation technology for timber, mineral, and oil industry in Alaska, Canada, Northern Europe, and Russia. Construction techniques tend to be simple and are usually some combination of traffic compaction, various drags, compaction rollers, and sometimes water spray on compacted surfaces. In the past, compacted snow runways have been used to support wheeled aircraft in the general range of 70 to 100 tons in support of research activities in Greenland and Antarctica (Bender 1957, Coffin 1966, Moser and Sherwood 1966, Aver'yanov 1985, and Antarctic Treaty Consultative Meeting 2002). Some of these were compacted snow over deep snow foundations while others were compacted snow over ice. Abele (1990) provides a comprehensive review of snow roads and runways and includes criteria for compacted snow strength to support aircraft operations. The required snow strength needed to support aircraft operation is considerably higher than that required for unsurfaced soils and no explanation is readily available for this dichotomy (Rollings and Rollings 2001). This merits further investigations.

It is feasible to build up the needed required strength to support aircraft in a layered, compacted snow runway. However, it is a lengthy process with delays between lifts to allow hardening of the snow (Abele 1990, Reese 1955), and the required strength criteria needs serious review to determine why the current requirements are much higher than for unsurfaced soil and to insure that they are valid. Recent work with thin compacted snow layers at Pegasus Runway at McMurdo Station illustrates another potential application for compacted snow for expedient military airfields.

Pegasus Runway is one of three air facilities supporting McMurdo Station, Antarctica. It is an ice runway located on the Ross Ice Sheet, a floating glacial ice sheet approximately 100-feet thick. This runway is described in detail by Blaisdell et al (1998), but the intense 24-hr austral sun caused some problems with near surface melting and resulting surface problems. A thin compacted snow layer was considered as a reflective protective surfacing but would have to support wheeled aircraft with tire pressures in the approximate range of 100 to 200 psi for C-130, C-5, C-17, and C-141 aircraft. An initial small trial area of compacted snow in the 2000-2001 austral summer season appeared promising. In the 2001-2002 season, Pegasus Runway was surfaced with approximately 3 in. of compacted snow. Operations in the 2001-2002 and 2002-2003 seasons were quite successful (Figures 5 and 6). Extensive trials with C-130, C-17, and C-141 aircraft with supporting fieldwork by teams from Air Mobility Command, AF Civil Engineering Support Agency (AFCESA), and Cold Regions Research and Engineering Laboratory during the 2001-2002 season developed a nomograph for evaluating the required strength of the compacted snow (Figure7). Guidance for design, building, maintaining, and evaluating a compacted snow runway surface over a structural ice runway were published in an USAF Engineering Technical Letter (AFCESA 2002).

While a similar snow protective layer may be useful on any ice runway, it also could be used as a leveling surface for uneven frozen ground. It would be difficult to grade a frozen soil to the tolerances required for aircraft. However, it would be feasible to use compacted snow to remove frozen soil surface irregularities. Essentially, the compacted snow serves as a thin surface layer to provide a smooth operational surface without rutting, and the frozen ground provides the structural support. This is analogous to the roles played by the asphaltic concrete surface and the underlying structural base and subbase courses in a conventional flexible pavement.

SNOW CONTROL

Snow often accompanies the cold temperatures needed for formation of ice and frozen ground that we would like to exploit for possible expedient military airfields. As noted earlier compacted snow has potential usefulness as a surfacing and pavement medium for the military engineer, but it has at least two drawbacks that must be considered. Snow is an insulator so progression of freezing of lake or sea ice or ground will be slowed by snow cover. Conversely, it also impedes thawing when the weather begins to warm. In order to speed the freezing process, the snow may have to be removed; this can be an onerous task. Blowing snow can also form drifts that cover the desired airfield surface and impede operations. Hence snow clearing and snow control structures may prove necessary.

REPAIRS

Surface defects in ice-, snow-, or frozen-ground airfield pavement can be readily repaired by compacting snow or allowing water to freeze in the pothole, depression, etc. It may be possible to carry out similar repairs to damaged conventional pavements, but this is somewhat more problematic than for ice, frozen ground, or snow pavements. Both asphaltic concrete and portland-cement concrete will tend to warm faster than the other mediums we have discussed and repairs may tend to melt except in particularly cold conditions. One should note that simply filling a defect with water and allowing it to freeze will seldom be satisfactory. The expansion of the water will usually cause the repair to pop out. Adding ice chunks or aggregate if available and progressively filling and freezing the repair in layers has given more satisfactory results. Blaisdell et al (1998) and AFCESA (2002) provide some recommended procedures that have worked for such repairs.

CONCLUSIONS

Construction of expedient military airfield facilities under conditions of continuous cold is a difficult task, and military guidance for such undertakings is scarce. However, recent experience supporting research efforts in the Antarctic and industrial work in the Arctic have developed techniques that the military engineer could adapt for expedient military airfields. These include:

(1) Glacial-, lake-, river-, and sea-ice runways and parking areas. This option is largely limited to the far northern regions but can provide airfields for lengthy periods of the year.

(2) Accelerated development of adequate ice thickness through flooding, ice aggregate, or spray ice techniques. This significantly expands the potential area where ice pavement facilities could be used.

(3) Unsurfaced frozen ground.

(4) Compacted snow as smooth surfaces over ice or frozen ground.

More work is needed to develop guidelines and demonstrate the efficacy and limitations of these approaches, but the potential exists. Since the military engineer never knows from where the next challenge may come, it would seem prudent to have these options available for use when needed.

ACKNOWLEDGMENTS

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Table 1. Estimated Soil Conditions and C-130 Operations for Minot AFB Example

Soil Condition	Estimated Soil CBR	Estimated C-130 Coverages
Wet	2	0
Average	7	1.5
Dry	11	27
Thawed	<1	0
Frozen	?	?

Notes: 1. Avergae conditions correspond to equilibrium mc and CBR under paved areas.
2. Estimate of C-130 coverages based on criteria in Ladd (1970)

FIGURE 1 C-5 Landing on Sea-Ice Runway, McMurdo Station, Antarctica

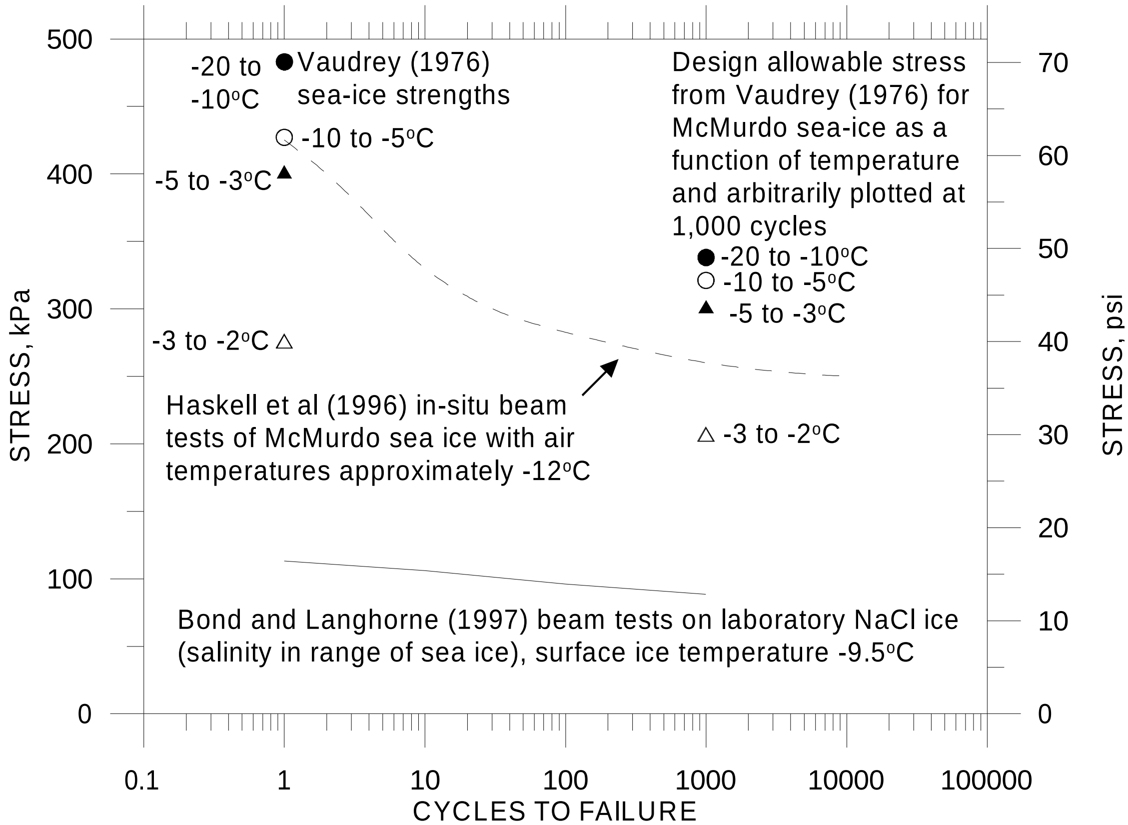

FIGURE 2 Examples of Fatigue Relations for Sea-Ice

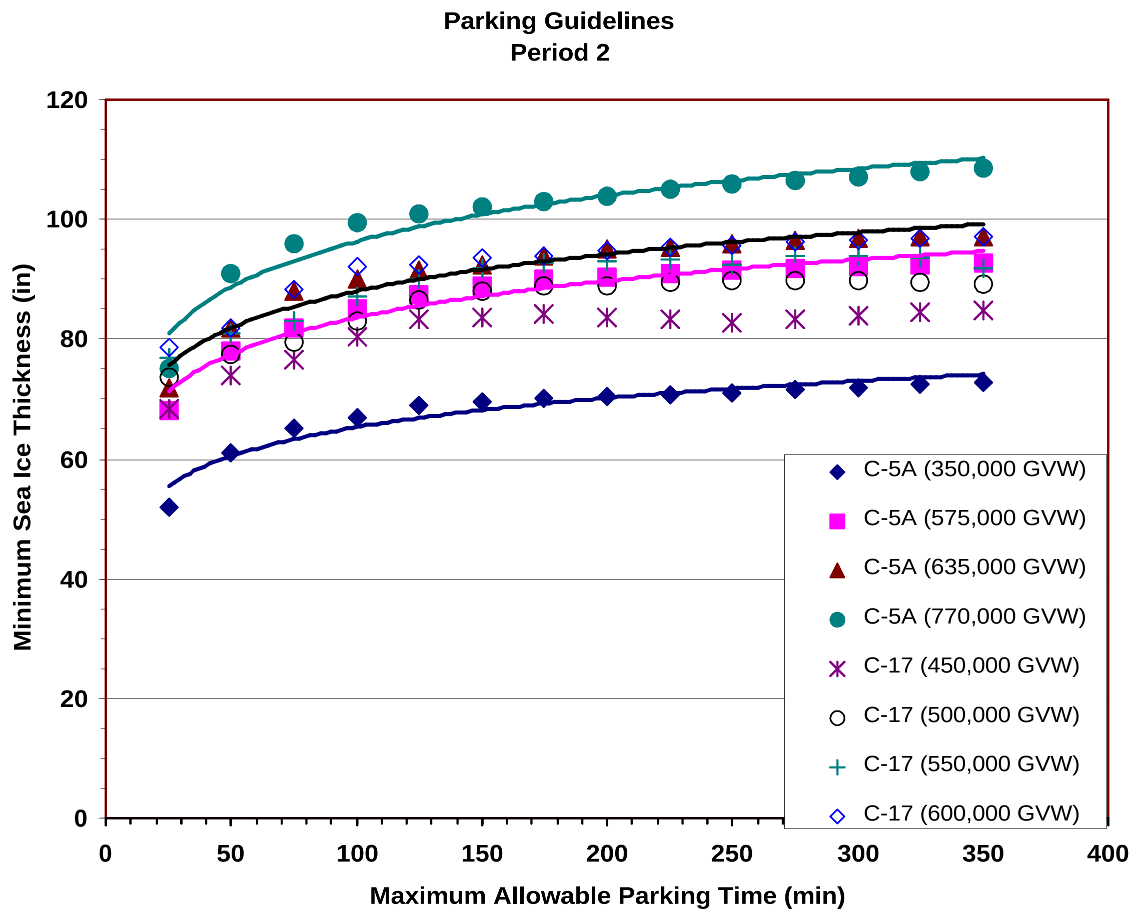

FIGURE 3 Example of Parking Guidelines Because of Creep Deformations During Periods when Temperature is -5 to -10°C, McMurdo Station Sea-Ice Runway

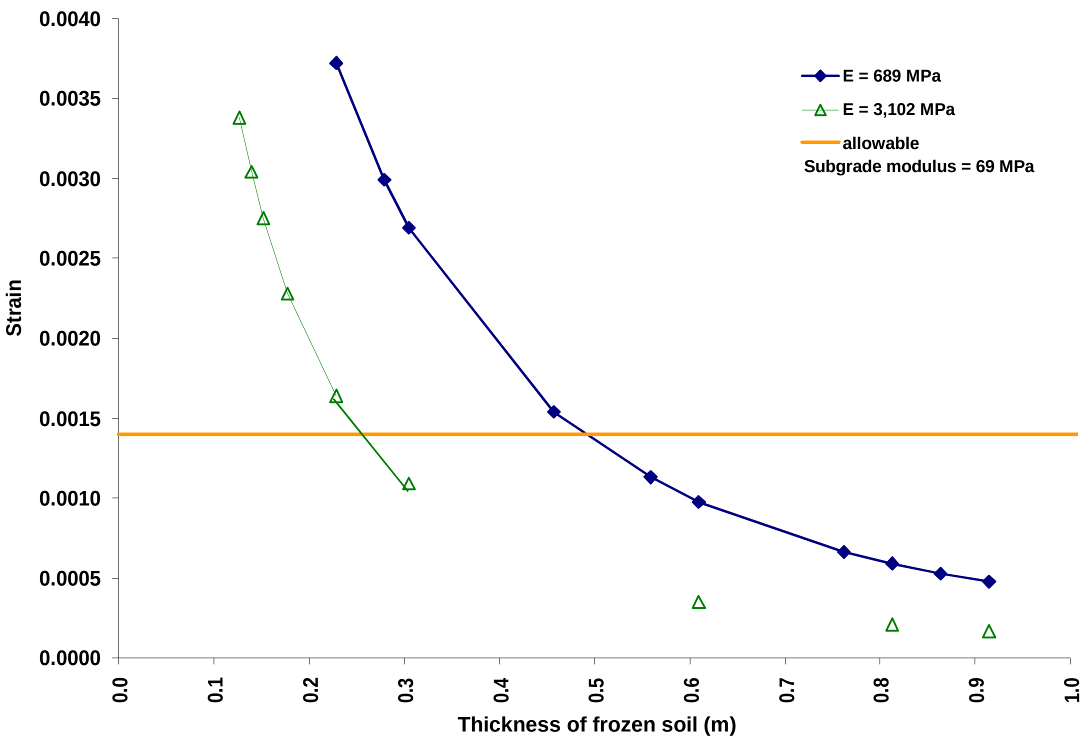

FIGURE 4 Calculation of Required Thickness of Frozen Ground for 10,000 C-130 Passes, Minot AFB Example

FIGURE 5 C-17 Landing on Compacted Snow Surface, Pegasus Runway, McMurdo Station, Antarctica

Figure 6. Tire Tracks from C-141 (195 ps tire pressure) in Compacted Snow, Pegasus Runway

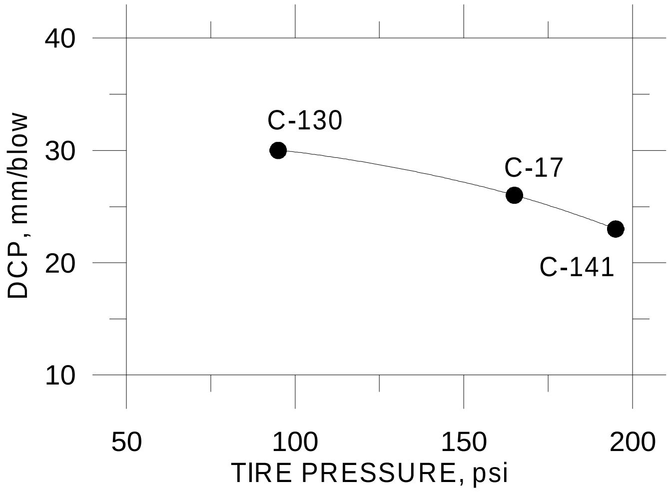

FIGURE 7 Dynamic Cone Penetrometer Requirements for Compacted Snow Operations